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DESCRIPTION

LASER PROCESSING METHOD AND DEVICE

Technical Field

5 [0001] The present invention relates to a laser processing method and laser processing apparatus for processing an object to be processed by irradiating the object with a laser beam.

Background Art

10 [0002] Known as a conventional laser processing technique is one in which measurement means (a contact-type displacement meter, an ultrasonic rangefinder, or the like) for measuring the main surface height of the object to be processed is arranged in parallel with a condenser lens for converging a laser beam with a predetermined gap therebetween (see, for example, Figs. 6 to 10 of Patent Document 1). In such a laser processing technique, while scanning the object with the
15 laser beam along its main surface, the main surface height of the object is measured by the measurement means, and the condenser lens is driven along its optical axis such that the distance between the condenser lens and the main surface of the object becomes constant according to thus measured main surface at the time when the
20 measurement point is positioned directly under the condenser lens.

[0003] Known as a technique for processing an object to be processed whose main surface has irregularities, on the other hand, is one in which the planarity in the whole part to be processed is measured by planarity measuring means (a planarity meter comprising a projector and a
25 reflected light receiver) as a preparation for processing, and the object is processed according to thus measured planarity (see, for example,

Patent Document 2).

Patent Document 1: Japanese Patent Application Laid-Open No.
2002-219591

Patent Document 2: Japanese Patent Application Laid-Open No. HEI
11-345785

Disclosure of the Invention

Problem to be Solved by the Invention

[0004] However, the following problem to be overcome exists in the
above-mentioned laser processing apparatus disclosed in Patent
Document 1. When the laser beam irradiation is started from a
position on the outside of the object to be processed, so as to perform
processing while the laser beam and the object are moved along the
main surface of the latter, the measurement means proceeds with
measurement from the outside of the object to the inside thereof.

When the condenser lens is driven according to the measured value of
main surface height obtained by this measurement, the converging point
of the laser beam may deviate from its predetermined position in end
parts of the object to be processed.

[0005] Though the planarity of the main surface of the object to be
processed can accurately be grasped when the technique disclosed in
Patent Document 2 is used, the same part must be scanned twice, i.e.,
before and during the actual processing, which takes time and lowers
the processing efficiency.

[0006] Therefore, it is an object of the present invention to provide a
laser processing method and laser processing apparatus which can
efficiently perform laser processing while minimizing the deviation of

the laser beam converging point in the end parts of the object.

Means for Solving Problem

[0007] The inventors conducted various studies in order to overcome the above-mentioned problem. First, a processing method in which a first laser beam for processing and a second laser beam for measuring the displacement of a main surface of an object to be processed are emitted to the object on the same axis was studied. Details of this study will now be explained with reference to Figs. 10(A) to 10(C).

[0008] Fig. 10(A) shows a processing preparatory phase in the case where a silicon wafer 800 secured to a dicing film 802 is processed with a laser beam emitted from a laser unit 804. The laser unit 804 includes a condenser lens 804a for converging the laser beam onto the silicon wafer 800, a lens holder 804b for holding the condenser lens 804a, and a piezoelectric actuator 804c which holds the lens holder 804b such that the latter can freely advance and retract with respect to the silicon wafer 800. The laser processing apparatus including the laser unit 804 further comprises a laser light source and the like which are not described. In the state of Fig. 10(A), irradiation with a first laser beam 806 for processing and a second laser beam 808 for measuring the displacement of a main surface 800b of the silicon wafer 800 is started, while a stage (not depicted) mounting the silicon wafer 800 is moved such that the silicon wafer 800 shifts in the direction of arrow A. The silicon wafer 800 is to be processed with the first laser beam 806 at a position corresponding to a line to cut 800a.

[0009] As the silicon wafer 800 shifts in the direction of arrow A in Fig. 10(A), the optical axis of the first laser beam 806 and second laser beam

808 reaches a position where it intersects the silicon wafer 800. The piezoelectric actuator 804c causes the lens holder 804b to advance/retract with respect to the silicon wafer 800 such that an astigmatism signal detected from reflected light of the second laser beam 808 becomes a predetermined value. Therefore, the piezoelectric actuator 804c retracts from the state of Fig. 10(B), so as to raise the lens holder 804b and condenser lens 804a. However, since the silicon wafer 800 keeps shifting in the direction of arrow A in Fig. 10(A), a time lag occurs until the lens holder 804b and condenser lens 804a rise to a predetermined position so that the converging point of the first laser beam 806 is positioned at the line to cut 800a. Also, the astigmatism signal may vary so much that the converging point of the first laser beam 806 fluctuates.

[0010] Therefore, as shown in Fig. 10(C), a part other than the line to cut 800a is processed with the laser in an area B until the first laser beam 806 is in focus with the line to cut 800a so as to attain a stable state. For example, assuming that the silicon wafer 800 has a thickness of 100 μm , and that a time delay of 15 mS occurs, the length of the area B is theoretically 1.5 mm when the processing speed is 100 mm/S.

[0011] Though Figs. 10(A) to 10(C) relate to the silicon wafer 800 having an ideally high planarity, there may be a case where end parts are warped upward. An example of a silicon wafer having an end part warped upward will be explained with reference to Figs. 11(A) to 11(C).

[0012] Fig. 11(A) shows a processing preparatory phase in the case where a silicon wafer 810 secured to a dicing film 802 is processed with

a laser beam emitted from a laser unit 804. This laser unit 804 is the same as that explained with reference to Figs. 10(A) to 10(C). The silicon wafer 810 has an end part warped upward. A line to cut 810a in the silicon wafer 810 is set so as to be positioned equidistantly from a main surface 810b.

[0013] As the silicon wafer 810 shifts in the direction of arrow A in Fig. 11(A), the optical axis of the first laser beam 806 and second laser beam 808 reaches a position where it intersects the silicon wafer 810 as shown in Fig. 11(B). The piezoelectric actuator 804c causes the lens holder 804b to advance/retract with respect to the silicon wafer 810 such that an astigmatism signal detected from reflected light of the second laser beam 808 becomes a predetermined value. Therefore, the piezoelectric actuator 804c retracts from the state of Fig. 11(B), so as to raise the lens holder 804b and condenser lens 804a. However, since the silicon wafer 810 keeps shifting in the direction of arrow A in Fig. 11(A), a time lag occurs until the lens holder 804b and condenser lens 804a rise to a predetermined position so that the converging point of the first laser beam 806 is positioned at the line to cut 810a. Also, since an end part of the silicon wafer 810 is warped upward, the gap from the position of the dotted line C to the actual position of the main surface 810b in Fig. 11(B) causes an overshoot when the lens holder 804b and condenser lens 804a rise to the predetermined position.

[0014] Therefore, as shown in Fig. 11(C), a part other than the line to cut 810a is processed with the laser in an area D until the first laser beam 806 is in focus with the line to cut 810a so as to attain a stable state. The length of the area D tends to be longer by the overshoot

than the length of the area B in Fig. 10(C). Hence, the inventors take notice of the processing in end parts of the object to be processed. The present invention is achieved according to these findings.

[0015] The present invention provides a laser processing method for irradiating an object to be processed with a first laser beam while converging the first laser beam with a lens such that a converging point is positioned within the object, and forming a modified region within the object along a line to cut in the object; the method comprising (1) a displacement acquiring step of acquiring a displacement between a point on the line to cut and one end of the line to cut while irradiating the object with a second laser beam for measuring a displacement of a main surface of the object and detecting reflected light reflected by the main surface in response to the irradiation; (2) a position setting step of setting an initial position for holding the lens with ~~respect to the main~~ surface of the object according to the acquired displacement; and (3) a processing step of forming the modified region in one end part of the line to cut upon irradiation with the first laser beam while holding the lens at the initial position, releasing the lens from being held at the initial position after forming the modified region in the one end part, and then forming the modified region while adjusting the position of the lens.

[0016] The laser processing method of the present invention acquires the displacement between a point on the line to cut and one end of the line to cut, and sets the initial position for holding the lens according to the acquired displacement. Therefore, even when a change in the shape such as curvature is generated in an end part of the object, for

example, the lens can be held at an initial position conforming to such a state of the end part. Also, since the modified region is formed in one end part of the line to cut while the lens is held at the initial position, the modified region can be formed while minimizing the influence of fluctuations in the shape of end parts in the object. After the modified region is formed in one end part of the line to cut, the lens is released from being held, and the modified region is formed while adjusting the lens position, whereby the modified region can be formed at a predetermined position within the object.

[0017] It will be preferred in the laser processing method of the present invention if the second laser beam is emitted without emitting the first laser beam in the displacement acquiring step. Since the first laser beam is not emitted when acquiring the displacement of the main surface of the object to be processed, the displacement of the main surface of the object can be acquired without forming the modified region therein.

[0018] It will also be preferred in the laser processing method of the present invention if the first and second laser beams are converged by the lens so as to irradiate the object on the same axis. Since the first and second laser beams are converged by the lens so as to be emitted on the same axis, the converging point of the first laser beam can be prevented from deviating from a predetermined position within the object because of a vibration of a stage mounting the object, for example.

[0019] It will also be preferred in the laser processing method of the present invention if the displacement is acquired from a point on the line

to cut toward one end of the line to cut in the displacement acquiring step. When the displacement is acquired from the inner side to outer side of the line to cut, a continuously changing surface displacement is acquired, whereby the displacement can be obtained stably.

5 [0020] It will also be preferred in the laser processing method of the present invention if the quantity of reflected light of the second laser beam is also acquired in the displacement acquiring step, and the initial position is set according to the displacement at a location where an amount of change in the acquired quantity of light becomes an extreme value in the position setting step. Since the quantity of reflected light varies depending on the distance from the reflecting surface, the displacement of the main surface seems to be acute in the vicinity of the location where the amount of change in the quantity of reflected light becomes an extreme value. Therefore, assuming that this location corresponds to an outer edge of the main surface of the object to be processed, the initial position can be set according to the displacement of the main surface at the location.

20 [0021] It will also be preferred in the laser processing method of the present invention if the quantity of reflected light of the second laser beam is also acquired in the displacement acquiring step, and the initial position is set according to the displacement at a location where the acquired quantity of light becomes a predetermined threshold in the position setting step. The quantity of reflected light varies depending on the distance from the reflecting surface. Therefore, when a predetermined threshold is set to a value corresponding to the height of the main surface, and a location where the quantity of reflected light

becomes the predetermined threshold is assumed to correspond to an outer edge of the main surface of the object to be processed, the initial position can be set according to the displacement of the main surface at the location.

5 [0022] It will also be preferred in the laser processing method of the present invention if, in the processing step, the second laser beam is emitted to the main surface of the object to be processed, and the lens is released from being held at the initial position according to the quantity of reflected light reflected by the main surface in response to the
10 emission. The quantity of reflected light varies depending on the distance from the reflecting surface. Therefore, a location corresponding to an outer edge of the main surface of the object to be processed can be assumed according to the quantity of reflected light and, at this location, the lens can be released from being held at the
15 initial position.

[0023] It will also be preferred in the laser processing method of the present invention if, in the processing step, the lens is released from being held at the initial position after an amount of change in the quantity of reflected light becomes a maximum value. Since the
20 quantity of reflected light varies depending on the distance from the reflecting surface, the displacement of the main surface seems to be acute in the vicinity of the location where the amount of change in the quantity of reflected light becomes an extreme value. Therefore, assuming that this location corresponds to an outer edge of the main
25 surface of the object to be processed, the lens can be released from being held at the initial position after forming the modified region at the

location.

[0024] It will also be preferred in the laser processing method of the present invention if, in the processing step, the lens is released from being held at the initial position after the quantity of reflected light becomes a predetermined threshold. The quantity of reflected light varies depending on the distance from the reflecting surface. Therefore, when a predetermined threshold is set to a value corresponding to the height of the main surface, and a location where the quantity of reflected light becomes the predetermined threshold is assumed to correspond to an outer edge of the main surface of the object to be processed, the lens can be released from being held at the initial position after forming the modified region at the location.

[0025] The present invention provides a laser processing apparatus for irradiating an object to be processed with a first laser beam while converging the first laser beam with a lens such that a converging point is positioned within the object, and forming a modified region within the object along a line to cut in the object; the apparatus comprising a lens for converging the first laser beam and a second laser beam for measuring a displacement of a main surface of the object onto the object; displacement acquiring means for acquiring the displacement of the main surface by detecting reflected light reflected by the main surface in response to irradiation with the second laser beam; moving means for moving the object and the lens relative to each other along the main surface; holding means for holding the lens such that the lens freely advances and retracts with respect to the main surface; and control means for controlling respective behaviors of the moving means

and holding means; wherein, while emitting the second laser beam, the control means controls the moving means so as to move the object and the lens relative to each other along the line to cut, the displacement acquiring means acquiring the displacement between a point of the line to cut and one end of the line to cut, the control means controlling the holding means so as to hold the lens at an initial position set according to the acquired displacement; wherein, while emitting the first laser beam with the lens being held at the initial position, the control means controls the moving means so as to move the object and the lens relative to each other along the line to cut, thereby forming the modified region in one end part of the line to cut; and wherein, after forming the modified region in the one end part, the control means controls the holding means so as to release the lens from being held at the initial position and hold the lens while adjusting a position of the lens, and controls the moving means so as to move the object and the lens relative to each other along the line to cut.

[0026] The laser processing apparatus of the present invention acquires the displacement between a point on the line to cut and one end of the line to cut, and holds the lens at the initial position based on the acquired displacement. Therefore, even when a change in the shape such as curvature is generated in an end part of the object, for example, the lens can be held at an initial position conforming to such a state of the end part. Also, since the modified region is formed in one end part of the line to cut while the lens is held at the initial position, the modified region can be formed independently of fluctuations in the shape of end parts in the object. After the modified region is formed in

one end part of the line to cut, the lens is released from being held, and the modified region is formed while adjusting the lens position, whereby the modified region can be formed while keeping a constant distance between the lens and the main surface of the object.

5 [0027] It will be preferred in the laser processing apparatus of the present invention if the second laser beam is emitted without emitting the first laser beam when the control means controls the moving means so as to move the object and the lens relative to each other along the line to cut while the displacement acquiring means acquires the
10 displacement between a point of the line to cut and one end of the line to cut. Since the first laser beam is not emitted when acquiring the displacement of the main surface of the object to be processed, the displacement of the main surface of the object can be acquired without forming the modified region therein.

15 [0028] It will also be preferred in the laser processing apparatus of the present invention if the lens converges the first and second laser beams onto the object on the same axis. Since the first and second laser beams are emitted on the same axis, the converging point of the first laser beam can be prevented from deviating from a predetermined
20 position within the object because of a vibration of a stage mounting the object, for example.

[0029] It will also be preferred in the laser processing apparatus of the present invention if the control means controls the moving means so as to irradiate the line to cut from a point thereof toward one end thereof
25 with the second laser beam, and the displacement acquiring means acquires the displacement from the point on the line to cut toward the

one end of the line to cut in response to the irradiation with the second laser beam. When the displacement is acquired from the inner side to outer side of the line to cut, a continuously changing surface displacement is acquired, whereby the displacement can be obtained stably.

[0030] It will also be preferred in the laser processing apparatus of the present invention if the displacement acquiring means also acquires the quantity of reflected light of the second laser beam, and the control means sets the initial position according to the displacement at a location where an amount of change in the acquired quantity of light becomes an extreme value. Since the quantity of reflected light varies depending on the distance from the reflecting surface, the displacement of the main surface seems to be acute in the vicinity of the location where an amount of change in the quantity of reflected light becomes an extreme value. Therefore, assuming that this location corresponds to an outer edge of the main surface of the object to be processed, the initial position can be set according to the displacement of the main surface at the location.

[0031] It will also be preferred in the laser processing apparatus of the present invention if the displacement acquiring means also acquires the quantity of reflected light of the second laser beam, and the control means sets the initial position according to the displacement at a location where the acquired quantity of light becomes a predetermined threshold. Since the quantity of reflected light varies depending on the distance from the reflecting surface, the displacement of the main surface seems to be acute in the vicinity of the location where the

amount of change in the quantity of reflected light becomes an extreme value. Therefore, assuming that this location corresponds to an outer edge of the main surface of the object to be processed, the initial position can be set according to the displacement of the main surface at the location.

[0032] It will also be preferred in the laser processing apparatus of the present invention if the control means controls the holding means so as to release the lens from being held at the initial position according to the quantity of reflected light of the second laser beam. The quantity of reflected light varies depending on the distance from the reflecting surface. Therefore, a location corresponding to an outer edge of the main surface of the object to be processed can be assumed according to the quantity of reflected light and, after forming the modified region at ~~this location~~, the lens can be released from being held at the initial position.

[0033] It will also be preferred in the laser processing apparatus of the present invention if the control means controls the holding means so as to release the lens from being held at the initial position after an amount of change in the quantity of reflected light becomes a maximum value. Since the quantity of reflected light varies depending on the distance from the reflecting surface, the displacement of the main surface seems to be acute in the vicinity of the location where the amount of change in the quantity of reflected light becomes an extreme value. Therefore, assuming that this location corresponds to an outer edge of the main surface of the object to be processed, the lens can be released from being held at the initial position after forming the modified region at the

location.

[0034] It will also be preferred in the laser processing apparatus of the present invention if the control means controls the holding means so as to release the lens from being held at the initial position after the quantity of reflected light becomes a predetermined threshold. The quantity of reflected light varies depending on the distance from the reflecting surface. Therefore, when a predetermined threshold is set to a value corresponding to the height of the main surface, and a location where the quantity of reflected light becomes the predetermined threshold is assumed to correspond to an outer edge of the main surface of the object to be processed, the lens can be released from being held at the initial position after forming the modified region at this location.

Effect of the Invention

[0035] The laser processing method and laser processing apparatus of the present invention can efficiently carry out laser processing while minimizing the deviation of the converging point of a laser beam in end parts of an object to be processed.

Brief Description of the Drawings

[0036] [Fig. 1] Fig. 1 is a view showing the configuration of the laser processing apparatus in accordance with an embodiment of the present invention.

[Fig. 2] Fig. 2 is a diagram showing a functional configuration of a control unit provided in the laser processing apparatus in accordance with the embodiment.

[Fig. 3] Fig. 3 is a view showing an object to be processed for explaining the embodiment.

[Fig. 4] Fig. 4 is a view for explaining the laser processing method in accordance with an embodiment of the present invention.

[Fig. 5] Fig. 5 is a chart for explaining the laser processing method in accordance with the embodiment.

5 [Fig. 6] Fig. 6 is a flowchart for explaining the laser processing method in accordance with the embodiment.

[Fig. 7] Fig. 7 is a view for explaining the laser processing method in accordance with the embodiment.

10 [Fig. 8] Fig. 8 is a chart for explaining the laser processing method in accordance with the embodiment.

[Fig. 9] Fig. 9 is a flowchart for explaining the laser processing method in accordance with the embodiment.

[Fig. 10] Fig. 10 is a view for explaining details of the studies led to the present invention.

15 [Fig. 11] Fig. 11 is a view for explaining details of the studies led to the present invention.

Explanations of Numerals

20 [0037] 1...laser processing apparatus, 2...stage, 3...laser head unit, 4...optical system main part, 5...objective lens unit, 6...laser emitting apparatus, 7...control unit, S...object, R...modified region, 42...processing objective lens, 43...actuator, 13...laser head, 44...laser diode, 45...light-receiving part.

Best Modes for Carrying Out the Invention

25 [0038] The findings of the present invention can easily be understood in view of the following detailed descriptions with reference to the accompanying drawings, which are represented for the purpose of

illustration only. Embodiments of the present invention will now be explained with reference to the accompanying drawings. When possible, parts identical to each other will be referred to with numerals identical to each other without repeating their overlapping explanations.

5 [0039] The laser processing apparatus in accordance with an embodiment of the present invention will be explained with reference to Fig. 1. As shown in Fig. 1, this laser processing apparatus 1 is one which irradiates a planar object to be processed S mounted on a stage 2 (moving means) with a processing laser beam L1 (first laser beam) such
10 that a converging point P is positioned within the object S, so as to form a modified region R caused by multiphoton absorption within the object S. The stage 2 is movable upward/downward and leftward/rightward and rotatable, whereas a laser emitting apparatus 6 mainly constituted by a laser head unit 3, an optical system main part 4, and an objective
15 lens unit 5 is disposed above the stage 2. The laser processing apparatus 1 also comprises a control unit 7 (control means), which outputs control signals for controlling behaviors of the stage 2 and laser emitting apparatus 6 (the movement of stage 2, emission of laser beams from the laser emitting apparatus 6, etc.) thereto.

20 [0040] The laser head unit 3 is detachably attached to an upper end part of the optical system main part 4. The laser head unit 3 includes an L-shaped cooling jacket 11. Embedded in a vertical wall 11a of the cooling jacket 11 is a cooling pipe 12 in a winding state, through which cooling water circulates. Attached to the front face of the vertical wall
25 11a are a laser head 13 which emits the processing laser beam L1 downward, and a shutter unit 14 for selectively opening and closing an

optical path of the processing laser beam L1 emitted from the laser head 13. This can prevent the laser head 13 and shutter unit 14 from overheating. For example, the laser head 13 uses an Nd:YAG laser and emits a pulsed laser beam having a pulse width of 1 μ s or shorter as the processing laser beam L1.

[0041] In the laser head unit 3, an adjuster 15 for adjusting the inclination of the cooling jacket 11 and the like is attached to the lower face of a bottom wall 11b of the cooling jacket 11. The adjuster 15 is used for aligning an optical axis α of the processing laser beam L1 emitted from the laser head 13 with an axis β which is set in the optical system main part 4 and objective lens unit 5 such as to extend vertically. Namely, the laser head unit 3 is attached to the optical system main part 4 by way of the adjuster 15. When the inclination of the cooling jacket 11 or the like is adjusted by the adjuster 15 thereafter, the inclination of the laser head 13 or the like is adjusted in conformity to the movement of the cooling jacket 11. As a consequence, the processing laser beam L1 advances into the optical system main part 4 while in a state where its optical axis α coincides with the axis β . The bottom wall 11b of the cooling jacket 11, the adjuster 15, and a housing 21 of the optical system main part 4 are formed with through holes through which the processing laser beam L1 passes.

[0042] On the axis β within the housing 21 of the optical system main part 4, a beam expander 22 for enlarging the beam size of the processing laser beam L1 emitted from the laser head 13, an optical attenuator 23 for adjusting the output of the processing laser beam L1, an output observation optical system 24 for observing the output of the processing

laser beam L1 adjusted by the optical attenuator 23, and a polarization adjusting optical system 25 for adjusting the polarization of the processing laser beam L1 are arranged in this order from the upper side to the lower side. A beam damper 26 for absorbing the eliminated laser beam is attached to the optical attenuator 23, and is connected to the cooling jacket 11 by way of a heat pipe 27. This can prevent the beam damper 26 having absorbed the laser beam from overheating.

[0043] For observing the object S mounted on the stage 2, a light guide 28 for guiding an observation visible ray is attached to the housing 21 of the optical system main part 4, whereas a CCD camera 29 is disposed within the housing 21. The observation visible ray is guided by the light guide 28 into the housing 21, successively passes through a field stop 31, a reticle 32, a dichroic mirror 33, and the like, and then is reflected by a dichroic mirror 34 disposed on the axis β . The reflected observation visible ray advances downward on the axis β and irradiates the object S. On the other hand, the processing laser beam L1 is transmitted through the dichroic mirror 34.

[0044] The reflected light beam of the observation visible ray reflected by a surface S1 of the object S advances upward on the axis β , and is reflected by the dichroic mirror 34. The light beam reflected by the dichroic mirror 34 is further reflected by the dichroic mirror 33, so as to pass through an imaging lens 35, etc., thereby entering the CCD camera 29. An image of the object S captured by the CCD camera 29 is displayed on a monitor (not depicted).

[0045] The objective lens unit 5 is detachably attached to the lower end part of the optical system main part 4. Since the objective lens unit 5

is positioned by a plurality of positioning pins with respect to the lower end part of the optical system main part 4, the axis β set in the optical system main part 4 and the axis β set in the objective lens unit 5 can easily be aligned with each other. By way of an actuator 43 (holding means) using a piezoelectric device, a processing objective lens 42 is mounted to the lower end of the housing 41 of the objective lens unit 5 while in a state where the optical axis coincides with the axis β . The housing 21 of the optical system main part 4 and the housing 41 of the objective lens unit 5 are formed with through holes through which the processing laser beam L1 passes. The peak power density of the processing laser beam L1 converged by the processing objective lens 42 is at least 1×10^8 (W/cm²) at the converging point P.

[0046] In order to position the converging point P of the processing laser beam L1 at a predetermined depth from the surface S1 of the object S, a laser diode 44 for emitting a rangefinding laser beam L2 (second laser beam) and a light-receiving part 45 (light-receiving means) are disposed within the housing 41 of the objective lens unit 5. The rangefinding laser beam L2 is emitted from the laser diode 44, and is successively reflected by a mirror 46 and a half mirror 47, and then by a dichroic mirror 48 disposed on the axis β . The reflected rangefinding laser beam L2 advances downward on the axis β , and passes through the processing objective lens 42, thereby irradiating the surface S1 of the object S. On the other hand, the processing laser beam L1 passes through the dichroic mirror 48.

[0047] The reflected light beam of the rangefinding laser beam L2 reflected by the surface S1 of the object S reenters the processing

objective lens 42, and advances upward on the axis β , so as to be reflected by the dichroic mirror 48. The reflected light beam of the rangefinding laser beam L2 reflected by the dichroic mirror 48 passes through the half mirror 47, so as to enter the light-receiving part 45, and is converged on a four-divided position detecting device (displacement acquiring means) in which a photodiode is equally divided into four. According to the converged image pattern of the reflected light beam of the rangefinding laser beam L2 converged onto the four-divided position detecting device, it can be detected where the converging point of the rangefinding laser beam L2 due to the processing objective lens 42 is positioned with respect to the surface S1 of the object S. Information about the converged image pattern of the reflected light beam of the rangefinding laser beam L2 converged on the four-divided position detecting device is outputted to the control unit 7. According to this information, the control unit 7 outputs a control signal for indicating to the actuator 43 a position for holding the processing objective lens 42.

[0048] Physically, the control unit 7 comprises an interface for exchanging signals with the stage 2 and laser emitting apparatus 6, a CPU (central processing unit), and a storage device such as memory or HDD. According to a program stored in the storage device, the CPU performs a predetermined information processing operation and outputs results of the information processing as control signals to the stage 2 and laser emitting apparatus 6.

[0049] Fig. 2 shows a functional configuration of the control unit 7. Functionally, as shown in Fig. 2, the control unit 7 comprises a laser

emission controller 701, a stage movement controller 702, an actuator controller 703, a converging point calculator 704, and an end part determiner 705. The laser emission controller 701 is a part which outputs signals for controlling emissions of the processing laser beam L1 and rangefinding laser beam L2 to the laser head 13 of the laser head unit 3 and the laser diode 44 of the objective lens unit 5, respectively. The stage movement controller 702 is a part which outputs a control signal for controlling the movement of the stage 2 thereto. The actuator controller 703 is a part which outputs a control signal for controlling the driving of the actuator 43 of the objective lens unit 5 to the actuator 43. The converging point calculator 704 is a part which calculates the distance between the object S and the converging point of the rangefinding laser beam L2 according to an astigmatism signal outputted from the light-receiving part 45 of the objective lens unit 5. The end part determiner 705 is a part which determines whether the processing objective lens 42 is at a position corresponding to an end part of the object S or not according to the quantity of light received by the light-receiving part 45. Operations of the individual functional constituents will be explained later.

[0050] An outline of a laser processing method carried out by thus configured laser processing apparatus 1 will now be explained. First, the object S is mounted on the stage 2, and the stage 2 is moved such that the converging point P of the processing laser beam L1 is positioned within the object S. The initial position of the stage 2 is determined by the thickness and refractive index of the object S, the numerical aperture of the processing objective lens 42, etc.

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[0051] Subsequently, the processing laser beam L1 is emitted from the laser head 13, the rangefinding laser beam L2 is emitted from the laser diode 44, and the stage 2 is moved such that the processing laser beam L1 and rangefinding laser beam L2 converged by the processing objective lens 42 scan a desirable line (line to cut) of the object S. Here, the light-receiving part 45 detects the reflected light beam of the rangefinding laser beam L2, and the control unit 7 controls the actuator 43 in a feedback fashion such that the converging point P of the processing laser beam L1 is always positioned at a predetermined depth from the surface S1 of the object S, whereby the position of the processing objective lens 42 is minutely adjusted along the axis β .

[0052] Therefore, even when the surface S1 of the object S wobbles, for example, a modified region R caused by multiphoton absorption can be formed at a position located at a predetermined depth from the surface S1. Forming the linear modified region R within the planar object S as such can generate a cleavage from the linear modified region R acting as a start point, whereby the object S can be cut easily with a high precision along the linear modified region R.

[0053] The laser processing method using the laser processing apparatus 1 of this embodiment will be explained more specifically. The explanation of the laser processing method will also illustrate operations of the laser processing apparatus 1.

[0054] The laser processing method in accordance with this embodiment can be divided into a preparatory step of emitting only the rangefinding laser beam L2 for measuring the displacement of the surface (main surface) S1 of the wafer-shaped object S, and a

processing step of emitting both the processing laser beam L1 and rangefinding laser beam L2. Each of the preparatory step and processing step will be explained.

[0055] (Preparatory Step) First, the preparatory step of emitting only the rangefinding laser beam L2 will be explained.

[0056] Fig. 3 is a plan view of the object S. In the object S, n lines to cut C_1 to C_n are set. In the processing step, which will be explained later, laser processing is performed at each of the lines to cut C_1 to C_n . In the preparatory step, the displacement of the surface S1 of the object S at an end part of each of the lines to cut C_1 to C_n is acquired, and the initial position of the processing objective lens 42 (see Fig. 1) is set according to thus acquired displacement. In the line to cut C_1 , for example, the displacement from a point Q_1 on the line to cut C_1 to one end thereof on the left side in the drawing is acquired, the initial position of the processing objective lens 42 (see Fig. 1) is set according to thus acquired position, and the stage 2 is moved such that the processing objective lens 42 at this initial position is located at a point X_1 on an extension of the line to cut C_1 . More detailed explanations will be set forth with reference to Figs. 4(A) to 4(C).

[0057] Figs. 4(A) to 4(C) are views showing the cross section II-II of Fig. 3. For easier understanding, the hatching indicating the cross section is omitted in Figs. 4(A) to 4(C). As shown in Fig. 4(A), the object S is attracted and secured to the stage 2 by way of a dicing film 2a. The dicing film 2a is secured with a dicing ring (not depicted). As shown in Fig. 4(A), the stage 2 moves such that the processing objective lens 42 is placed at a position corresponding to the point Q_1 on

the line to cut C_1 in the object S. The actuator 43 holding the processing objective lens 42 is in a state expanded by $25\text{ }\mu\text{m}$ from the most contracted state. This amount of expansion, i.e., $25\text{ }\mu\text{m}$, is set as one half of the maximum amount of expansion of the actuator 43, i.e., $50\text{ }\mu\text{m}$. In this state, the stage 2 is moved up/down so that a reflected light beam of the observation visible ray is in focus.

[0058] Subsequently, as shown in Fig. 4(B), the stage 2 is further raised by a predetermined distance (hereinafter referred to as processing height) from the state of Fig. 4(A), such that the distance between the surface S1 of the object S and the processing objective lens 42 is set shorter by the processing height than the distance in Fig. 4(A). Here, assuming that the focal point of the visible range and the converging point of the laser beam coincide with each other, the processing laser beam L1 is converged at a position corresponding to the value of product of the processing height from the surface S1 and the refractive index of the object S at the laser wavelength within the object S. When the object S is a silicon wafer having a refractive index of 3.6 (at a wavelength of $1.06\text{ }\mu\text{m}$) and a processing height of $10\text{ }\mu\text{m}$, for example, the processing laser beam L1 is converged at a position of $3.6 \times 10 = 36\text{ }\mu\text{m}$. An astigmatism signal is obtained from the reflected light beam of the rangefinding laser beam L2 in the state shown in Fig. 4(B), and the value of this astigmatism signal is employed as a reference value. While adjusting the amount of expansion/contraction of the actuator 43 such that the astigmatism signal obtained from the reflected light beam of the rangefinding laser beam L2 becomes this reference value, the stage 2 is moved so as to shift the processing objective lens

42 in the direction of arrow E in Fig. 4(B). Namely, the amount of expansion/contraction varies depending on the displacement of the object S, whereby the displacement of the surface S1 of the object S is acquired.

5 [0059] From the state shown in Fig. 4(B) to the state shown in Fig. 4(C), the processing objective lens 42 moves from a position corresponding to the point Q_1 on the line to cut C_1 to a position corresponding to one end of the line to cut C_1 . During this period, the actuator 43 is adjusted such that the astigmatism signal obtained from the reflected light beam of the rangefinding laser beam L2 becomes the above-mentioned reference value. When the processing objective lens 42 comes out of the object S from the state shown in Fig. 4(C), the rangefinding laser beam L2 irradiates a part other than the object S, i.e., the dicing film 2a. ~~In the dicing film 2a,~~ the reflectance of the rangefinding laser beam L2 is lower, whereby the total quantity of the reflected light beam of the rangefinding laser beam L2 detected by the four-divided position detecting device in the light-receiving part 45 (see Fig. 1) decreases. Therefore, when the total light quantity detected by the four-divided position detecting device in the light-receiving part 45 (see Fig. 1) becomes smaller than a predetermined threshold, the processing objective lens 42 is assumed to be located at a position corresponding to one end of the line to cut C_1 (in the state corresponding to Fig. 4(C)), the amount of expansion of the actuator at this time is held and taken as the initial position. While holding the processing objective lens 42 at this initial position, the stage 2 is moved such that the processing objective lens 42 is positioned at the point X_1 on an extension of the line to cut C_1 ,

thus achieving a wait state.

[0060] Though the processing objective lens 42 located at a position corresponding to one end of the line to cut C_1 is detected according to the fact that the total light quantity detected by the four-divided position detecting device in the light-receiving part 45 (see Fig. 1) becomes smaller than a predetermined threshold in the foregoing explanation, this is not restrictive, whereby other criteria may also be employed. An example of such criteria will be explained with reference to Figs. 5(A) and 5(B). Fig. 5(A), whose ordinate and abscissa indicate the total light quantity detected by the four-divided position detecting device of the light-receiving part 45 (see Fig. 1) and time, respectively, is a chart recording the change in the total light quantity detected by the four-divided position detecting device of the light-receiving part 45 (see Fig. 1) in the states of Figs. 4(B) and 4(C). In this case, as mentioned above, it is determined that the processing objective lens 42 is located at a position corresponding to one end of the line to cut C_1 at the time when the light quantity becomes smaller than a predetermined threshold T_1 .

[0061] From the graph of Fig. 5(A), at predetermined intervals (e.g., at individual sampling points), the amount of change in difference obtained by subtracting the previous total light quantity value from the current total light quantity value is calculated. Thus obtained values are plotted in Fig. 5(B) whose ordinate and abscissa indicate the amount of change and time, respectively. In this case, a part exhibiting a negative peak seems to be a point where the change in the total light quantity is the largest, i.e., a part corresponding to the vicinity of the

center of an edge (outer edge) of the object S. Therefore, the amount of expansion/contraction of the actuator 43 can be fixed at that corresponding to this part.

[0062] Operations of the laser processing apparatus 1 in this preparatory step will be explained with reference to the flowchart shown in Fig. 6. The stage controller 702 of the control unit 7 outputs a control signal to the stage 2 such that the processing objective lens 42 moves to the point Q_1 on the C_1 (step S01). In response to the output of this control signal, the stage 2 moves. Further, the actuator controller 703 of the control unit 7 outputs a control signal to the actuator 43 so as to make the latter expand by $25\text{ }\mu\text{m}$ (step S02). In response to the output of this control signal, the actuator 43 expands by $25\text{ }\mu\text{m}$. In this state, ~~the stage 2 is moved up/down so that the observation visible ray is in focus therewith,~~ and a focal position of the observation visible ray is set, whereby the processing objective lens 42 and the object S attain the state explained with reference to Fig. 4(A) (step S03).

[0063] The stage movement controller 702 of the control unit 7 outputs a control signal to the stage 2 so as to make the latter rise by a predetermined processing height (e.g., $10\text{ }\mu\text{m}$) (step S04). In response to the output of this control signal, the stage rises by $10\text{ }\mu\text{m}$, whereby the processing objective lens 42 and the object S attain the state explained with reference to Fig. 4(B).

[0064] The laser emission controller 701 of the control unit 7 outputs a control signal to the laser diode 44 so as to make the latter emit the rangefinding laser beam L2 (step S05). In response to the output of

this control signal, the laser diode 44 emits the rangefinding laser beam L2, whereas its reflected light beam reflected by the surface S1 of the object S is received by the four-divided position detecting device in the light-receiving part 45. In response to the light received, signals are
5 outputted to the converging point calculator 704 and the end part determiner 705.

[0065] The converging point calculator 704 holds the value of astigmatism signal in this state as a reference value. An instruction signal is outputted to the actuator controller 703 so as to attain thus held
10 reference value (step S06). Subsequently, the stage movement controller 702 outputs a control signal to the stage 2 such that the processing objective lens 42 moves in the direction of arrow E in Fig. 4(B) on the line to cut C₁ in the object S (step S07). The stage 2 moves in response to the output of this control signal, whereas the
15 actuator 43 expands/contracts in response to the displacement of the surface S1 of the object S and holds the processing objective lens 42 such that the converging point of the rangefinding laser beam L2 is placed at the reference position.

[0066] According to the signal outputted from the light-receiving part
20 45, the end part determiner 705 determines whether the processing objective lens 42 is located at an end part of the object S or not (step S08). When it is determined that the processing objective lens 42 is located at an end part of the object S, the end part determiner 705 outputs an instruction signal to the actuator controller 703 so as to stop
25 making the actuator 43 expand/contract. In response to the output of this instruction signal, the actuator controller 703 outputs a control

signal to the actuator 43 so as to make the latter stop expanding/contracting and attain a held state (step S09). In response to the output of this control signal, the actuator 43 stops expanding/contracting. When the processing objective lens 42 is located at the point X_1 on an extension of the line to cut C_1 , the stage movement controller 702 outputs a control signal to the stage 2 so as to stop moving the latter (step S10).

[0067] (Processing Step) The processing step of emitting the processing laser beam L1 and rangefinding laser beam L2 will now be explained.

[0068] The explanation will be set forth with reference to Figs. 7(A) to 7(C) showing the cross section II-II of Fig. 3 as with Figs. 4(A) to 4(C). For easier understanding, the hatching indicating the cross section is omitted in Figs. 7(A) to 7(C). Subsequent to the state of Fig. 4(C), Fig. 7(A) shows a state where the processing objective lens 42 is in a wait state at the point X_1 on an extension of the line to cut C_1 . The actuator 43 is fixed at the amount of expansion set in Fig. 4(C). Namely, the holding state at step S09 is maintained. The processing laser beam L1 and rangefinding laser beam L2 are emitted in the state of Fig. 7(A). The stage 2 moves such that the processing objective lens 42 shifts in the direction of arrow F in the drawing.

[0069] As the processing objective lens 42 moves in the direction of arrow F in Fig. 7(A), it reaches a position intersecting the line to cut C_1 in the object S, thus attaining the state shown in Fig. 7(B). The rangefinding laser beam L2 is reflected less by the dicing film 2a so that the total quantity of light reflected thereby is smaller, whereas the total

quantity of reflected light increases in the object S. Namely, the total quantity of reflected light beam of the rangefinding laser beam L2 detected by the four-divided position detecting device in the light-receiving part 45 (see Fig. 1) increases, whereby it can be
5 determined that the processing objective lens 42 is located at the position intersecting the line to cut C_1 in the object S when the total quantity of reflected light beam exceeds a predetermined threshold. Therefore, when the total light quantity detected by the four-divided position detecting device in the light-receiving part 45 (see Fig. 1) is
10 greater than the predetermined threshold, the processing objective lens 42 is assumed to be located at a position corresponding to one end of the line to cut C_1 (in the state corresponding to Fig. 7(B)), and expansion amount control of the actuator 43 is started so as to release the expansion amount of the actuator from being held at this time, such that
15 the astigmatism signal becomes the reference value. Here, a modified layer is formed by a predetermined processing height in an area G (one end part) of Fig. 7(B).

[0070] Thereafter, the processing objective lens 42 moves along the line to cut C_1 , and a modified layer R is formed by the processing laser beam
20 L1. During this time, the actuator 43 is adjusted such that the astigmatism signal obtained from the reflected light beam of the rangefinding laser beam L2 becomes the above-mentioned reference value.

[0071] Though the processing objective lens 42 having reached a
25 position corresponding to one end of the line to cut C_1 is detected according to the fact that the total light quantity detected by the

four-divided position detecting device in the light-receiving part 45 (see Fig. 1) exceeds a predetermined threshold in the foregoing explanation, this is not restrictive, whereby other criteria may also be employed. An example of such criteria will be explained with reference to Figs.

5 8(A) and 8(B). Fig. 8(A), whose ordinate and abscissa indicate the total light quantity detected by the four-divided position detecting device of the light-receiving part 45 (see Fig. 1) and time, respectively, is a chart recording the change in the total light quantity detected by the four-divided position detecting device of the light-receiving part 45 (see
10 Fig. 1) corresponding to Figs. 7(B) and 7(C). In this case, as mentioned above, it is determined that the processing objective lens 42 is located at a position corresponding to one end of the line to cut C_1 at the time when the light quantity exceeds a predetermined threshold T_2 .

[0072] From the graph of Fig. 8(A), at predetermined intervals (e.g., at
15 individual sampling points), the amount of change in difference obtained by subtracting the previous total light quantity value from the current total light quantity value is calculated. Thus obtained values are plotted in Fig. 8(B) whose ordinate and abscissa indicate the amount of change and time, respectively. In this case, a part exhibiting a
20 positive peak seems to be a point where the change in the total light quantity is the largest, i.e., a part corresponding to the vicinity of the center of an edge (outer edge) of the object S. Therefore, the tracking of the actuator 43 can be started after the differential peak shown in Fig. 8(B) stops changing after the total light quantity shown in Fig. 8(A) becomes the threshold T_2 .
25

[0073] Operations of the laser processing apparatus 1 in this processing

step will be explained with reference to the flowchart shown in Fig. 9. Here, the stage 2 and processing objective lens 42 of the laser processing apparatus 1 are assumed to be in the state explained with reference to Fig. 7(A) after being subjected to the preparatory step.

5 [0074] The laser emission controller 701 of the control unit 7 outputs control signals to the laser head 13 and laser diode 44 so as to make them emit the processing laser beam L1 and the rangefinding laser beam L2, respectively (step S11). In response to the output of the control signals, the processing laser beam L1 and the rangefinding laser beam
10 L2 are emitted.

[0075] The stage controller 702 of the control unit 7 outputs a control signal to the stage 2 so as to move the processing objective lens 42 in the direction of arrow F in Fig. 7(A) (step S12). In response to the output of this control signal, the stage 2 ~~starts moving~~.

15 [0076] According to the signal outputted from the light-receiving part 45, the end part determiner 705 of the control unit 7 determines whether the processing objective lens 42 is located at an end part of the object S or not (step S13). When it is determined that the processing objective lens 42 is located at an end part of the object S, the end part determiner
20 705 outputs an instruction signal to the actuator controller 703 so as to make the latter start the expansion/contraction of the actuator 43 such that the astigmatism signal equals the held reference value. The actuator controller 703 outputs the control signal to the actuator 43 so as to make the latter start expanding/contracting in order for the
25 astigmatism signal to equal the held reference value (step S14). In response to the output of this control signal, the actuator 43

expands/contracts according to the displacement of the surface S1 of the object S, and holds the processing objective lens 42 such that the converging point of the rangefinding laser beam L2 is located at the reference position. Therefore, the modified region R is formed at a position corresponding to the displacement of the surface S1 of the object S (see Fig. 7(C)). After the forming of the modified region along the line to cut C₁ and the processing objective lens 42 moves out of the object S, the stage movement controller 702 outputs a control signal to the stage 2 so as to make the latter stop moving (step S15).

[0077] The above-mentioned preparatory step and processing step are performed for all the lines to cut C₁ to C_n in the object S, whereby respective modified regions R are formed along the lines to cut C₁ to C_n.

[0078] In this embodiment, while adjusting the distance between the processing objective lens 42 and the object S such that the astigmatism signal acquirable from the reflected light beam of the rangefinder laser beam L2 becomes a predetermined value, the processing objective lens 42 is moved from a point on a line to cut in the object S toward one end of the line to cut, and an initial position is set while holding the distance between the processing objective lens 42 and the object S in an end part of the object S. Therefore, even when an end part of the object S is curved or the thickness of the object S varies, the processing objective lens 42 can be held at an initial position in conformity to such a change in the shape.

[0079] Since the laser processing is started by emitting the processing laser beam L1 while holding the processing objective lens 42 at this initial position, the influence of the change in the shape of the end part

of the object S can be excluded as much as possible.

[0080] After the modified region is formed in an end part of the object S while the processing objective lens 42 is held at the initial position, the processing objective lens 42 is released from being held, and then the modified region is formed while the distance between the processing objective lens 42 and the object S is adjusted so as to become constant, whereby the modified region can stably be formed at a position distanced from the surface S1 of the object S by a predetermined distance.

[0081] Since the modified region can stably be formed along the line to cut, when cutting/separating a wafer, which is an object to be processed, into chips by expanding the dicing film 2a and so forth after forming the modified region, the wafer can always be cut stably with a favorable cutting quality even when cutting a large amount of wafer.

Industrial Applicability

[0082] The laser processing method and laser processing apparatus of the present invention can efficiently carry out laser processing while minimizing the deviation of the converging point of a laser beam in end parts of an object to be processed.